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Strength Measurements of B3 (ODM) Dipoles

Bruce C. Brown
Main Injector Department, Beams Division
Fermi National Accelerator Laboratory *
P.O. Box 500
Batavia, Illinois 60510

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Abstract

Main Ring B3 (ODM) dipoles are required in several places in the current Fermilab accelerator complex. This note will provide some information on their strength based on both recent and previous measurements. Information on magnet fabrication history including identification of steel will be provided. This should preserve some lore until a more careful report can be prepared. Recent measurements of ODM006-1 (3006-1) and ODM032-1 (3032-1) will be combined with previous measurements to provide information on ODM009 from its most recent measurement. We find that the linear fields of these magnets is well described by the design gap of 3″ and an effective length of 239″. Non-linear contributions from remanent fields and saturation are documented. Some results on the variation from magnet to magnet are provided.

1 Introduction

The dipole magnets which were designed for creating overpasses in the Main Ring lattice are now in more general use. These 20 foot long magnets have a nominal aperture of 3″ $\times$ 5″. In Main Ring tradition, they were designated as the 3000 series or B3 Main Ring dipoles. For measurement with the VAX-CAMAC system at MTF, they were called the ODM series. They were designed by Stan Snowdon and an initial report on their design and use was provided by Frank Turkot[1].

The fabrication of these magnets was initiated for the D0 overpass project in 1984. Additional magnets were fabricated for the B0 overpass in the Main Ring, for the D0 overpass upgrade and for Main Ring aperture improvements and additional spares. A total of 30 magnets have been fabricated up to this time. Table 1 provides an overview of the fabrication history. The naming of these devices has been complicated by the various traditions in use. Other Main Ring dipoles and quadrupoles were given a new name when they were re-built. However, the advantages of maintaining the identity were obvious and resulted in some names being re-used for rebuilt ODM dipoles. The system of rework numbers associated with the MTF Unix-Sybase (CHISOX) measurement system is only starting to be used for these magnets. ODM025 was built using ODM009 cores and was rebuilt into ODM009. ODM026 was built from the ODM004 cores.

The failure rate of ODM dipoles was unacceptable. Two committees examined this problem. A 1989 committee[2] found quality control problems. A 1993 committee[3] discovered that failures were associated with

Serial Range	Steel Source	Year	Purpose
001-005	MR Armco+TeVI	1984	First D0 Overpass
006-012	TeVI	1986	B0 Overpass
013	MR Armco	1986	B0 Overpass
014-016	TeVI	1986	B0 Overpass
017-024	Inland	1988	Enhance D0 Overpass
025-026			Rebuilds
027-032	New Armco	1990	Aperture Improvements

Table 1: Some Properties of ODM Dipole Cores

high power operation and that the coil which did not fail was partly cooled by contact with the iron[4]. In light of this evidence that the cooling design was inadequate[5], a new design[6] was implemented and three magnets (ODM009, ODM032, ODM006) have been built with this new coil design.

Measurements of the five initial dipoles were made using a version of the original Main Ring measurement system. Some data from those measurements is available in TM-1302[1]. Subsequent magnets were measured with the VAX-CAMAC FLATCOIL program using Tevatron 2-wire dipole stretched wire fixtures and with the HARMONICS program using a specially constructed large diameter probe(2.6″ dia., 96″ coil length, Electronic ID. #13). For two recently built magnets, this measurement protocol was re-implemented and enhanced using the CHISOX measurement system. This document will provide some results for magnet strength (dipole field integral) using the VAX and CHISOX measurements. The 24 turn/pole main coils can be connected in series or in parallel depending upon the accelerator requirements. Some measurements with the series powering are available but the standard measurements are with parallel powering. Although the magnet includes a 20 turn/pole trim coil and measurements which powered that trim were made, we will not report on them here.

2 Remanent Field Measurements

FLATCOIL strength measurements record the flux change in a probe between 0 A excitation (remanent field) and some operating current. In Tevatron dipole measurements and in some recent CHISOX measurements, the remanent field is determined from the flux change observed by flipping (ro-

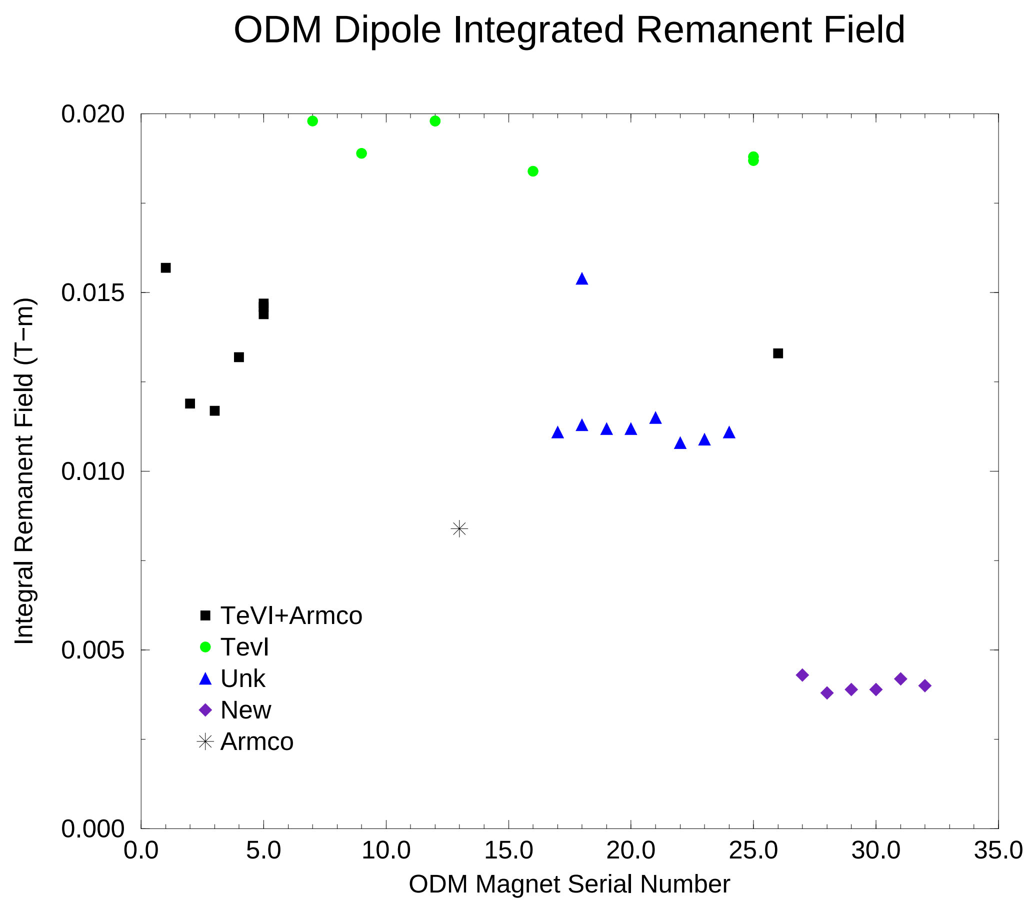

Figure 1: VAX-CAMAC HARMONICS Remanent Strength of ODM Dipoles

tating by 180°. This technique was not employed for the ODM magnets. The HARMONICS measurements of ODM dipoles (Procedure MRB0-3 in file MRB0-3_PROC.DOC;7) employed 3 transverse probe positions at each of 3 longitudinal positions. The resulting reference amplitudes for HARMONICS strength have been summed to provide a measure of the magnet strength based on assumptions about probe positioning and a constant steel length. These results were placed into the VAX-DATATRIEVE domain (file) HSUM from which results were extracted for this analysis. The sum

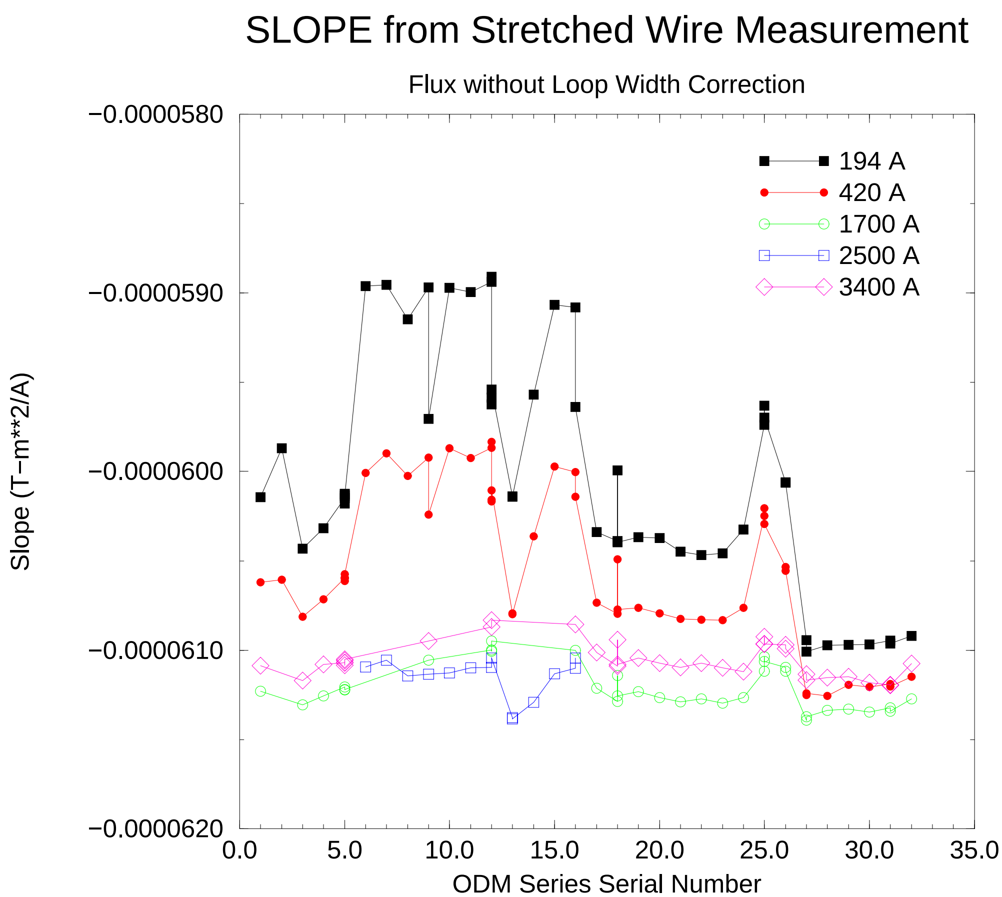

Figure 2: VAX-CAMAC Stretch Wire SLOPE. This is the flux change in ramping from 0 A to the designated current divided by the current change.

for ODM009 from the 1993 measurements was not available from HSUM so a remanent sum was made by hand. Figure 1 shows the available measurements.

We will employ the results shown in Figure 1 to add to the strengths measured using the stretched wire fixtures and FLATCOIL program so that we have the total integrated strength. We note that the measurements shown for the pairs (ODM009, ODM025) and (ODM004, ODM026) match in strength as befits results using the same cores. One incarnation measured

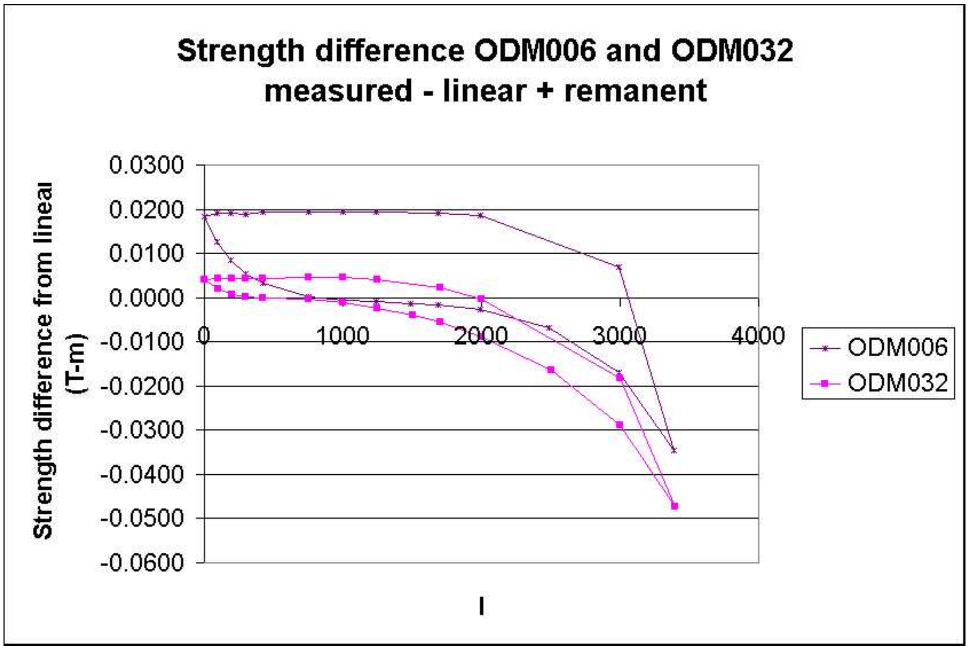

Figure 3: Non-linear Strength of ODM006-1 and ODM032-1 from CHISOX FLATCOIL measurements combined with estimate of remanent strength.

as ODM018 actually consisted of one half-core from ODM012 and one from ODM018. The resulting magnet had a remanent field integral of about the average of the two, as expected. Note that the reported remanent strength falls into groups which are consistent with the steel source grouping shown in Table 1. We have also plotted the results from FLATCOIL system measurements of a larger group of magnets in Figure 2. The groupings in Table 1 are re-confirmed from the 194 A and 420 A data in this plot. Additional discussion of iron differences and remanent fields can be found in MI-0015[7].

3 Recent Hysteretic Measurements

Two ODM magnets have been measured with the CHISOX measurement system. HARMONICS with the 2.6″ dia probe and 2-wire Stretched Wire measurements with the CHISOX FLATCOIL measurement protocol were carried out on ODM006-1 (3006-1) and ODM032-1 (3032-1). By fitting the downramp low field measurements to a straight line in our usual analysis

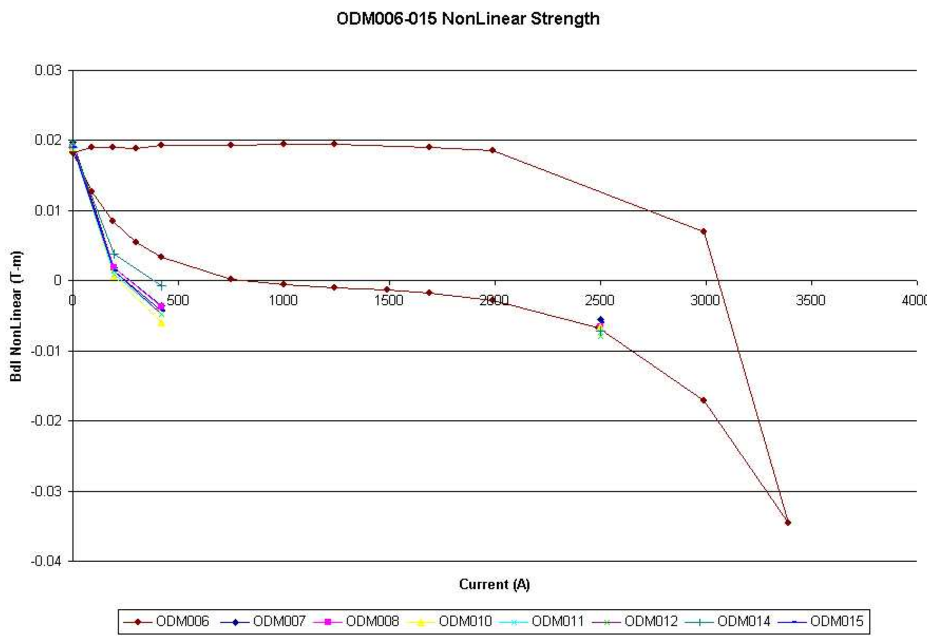

Figure 4: Non-linear strength of ODM dipoles from TeV I steel assuming non-linear field matches at 2500 A.

method[8], we obtain the linear strength of the magnet. Subtracting this from the measurements and adding in the remanent field enables us to determine the non-linear part of the integrated strength. This result is plotted in Figure 3. We note that the steel differences results in quite different non-linear fields at all energies. The hysteresis loop is more open for the TeV I steel (larger H_c) but the saturation effect is smaller.

4 Stretched Wire Results Assuming Uniform Steel

The advantages of measuring the low-field strength on the down ramp was not appreciated when the 1984 - 1993 measurements were made on these magnets. Additionally, Downramp FLATCOIL measurements were not handled properly by the VAX FLATCOIL software. Thus, to separate geometric and steel differences is more difficult. We will attempt this for some magnets which we group together. We will assume that the non-linear field at high fields is the same and adjust the linear term (L_{eff}/g). For the magnets

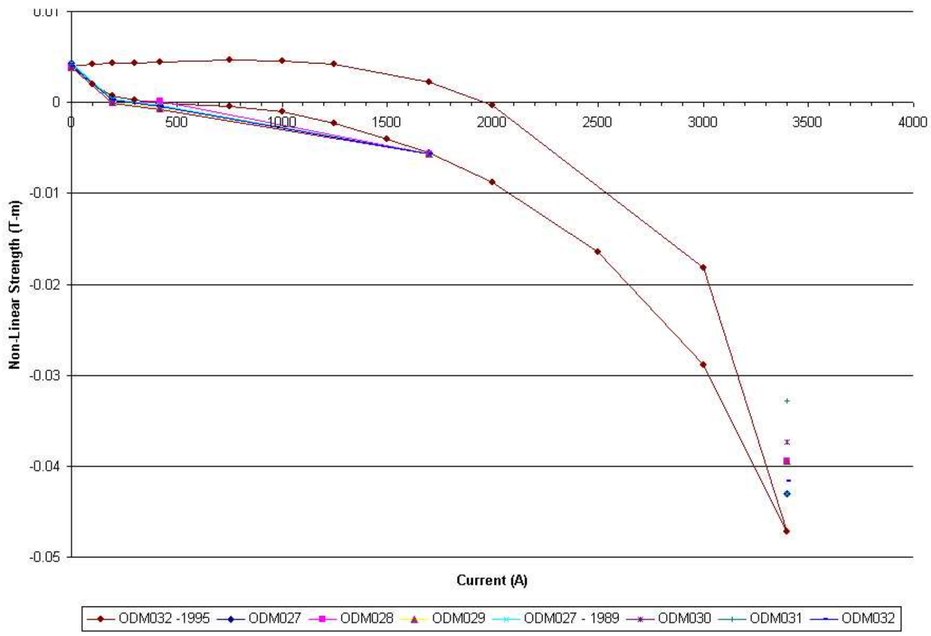

Figure 5: Non-linear strength of ODM027-032 dipoles assuming non-linear field matches at 1700 A.

constructed from the high H_c Tev I Project steel (B0 overpass), we employ the CHISOX measurements of ODM006-1 (3006-1) from December 1995. For this entire group of magnets we have HARMONICS measurements of remanent strength only for ODM007, 012 and 016 plus a measurement of ODM009 which has been processed differently. Nonetheless, from the uniformity shown in Figure 2, we are able to assign the typical value from those magnets with an uncertainty of only about 0.0005 T-m which will be unimportant for this analysis. The results in Figure 3 used this typical remanent strength (0.019 T-m) to analyze ODM006-1. Using an Excel spreadsheet, we obtain results from the 1986 stretched wire measurements of these dipoles by adding the measured or typical remanent field, then matching the non-linear field at 2500 A by adjusting the linear coefficient. The result is shown in Figure 4. We see that the match at low fields is not achieved but that nearly all the 1986 magnet measurements agree with each other on the 194 and 420 A non-linear field. The difference corresponds to a strength difference of about 0.5%. The source of this disagreement deserves (but will not

Serial	SW Fixture	Remanent (T-m)	GeomCorr
ODM006	9	0.019 **	1.0011
ODM007	9	0.0198	1.0005
ODM008	9	0.019 **	1.0020
ODM009	9	0.0189016	1.0014
ODM009	11	0.0189016	1.0014
ODM010	9	0.019 **	1.0017
ODM011	9	0.019 **	1.0014
ODM012	9	0.0198	1.0010
ODM013	9	0.0084	1.0014
ODM014	9	0.019 **	1.0045
ODM015	9	0.019 **	1.0017
ODM027	11	0.0043	1.00452
ODM027	11	0.0043	1.0042
ODM028	11	0.0038	1.00348
ODM029	11	0.0039	1.0034
ODM030	11	0.0039	1.00369
ODM031	11	0.0042	1.00337
ODM031	11	0.0042	1.00366
ODM032	11	0.004	1.00248

Table 2: Stretched wire fixture, integral remanent strength, and geometric correction used for above non-linear strength. ** indicates assumed rather than measured remanent. Loop width calibrations used are for Fixture 9, 0.025506109 m and for Fixture 11, 0.025498235 m.

receive here) further attention.

The same analysis technique is applied to magnets ODM027 - 032 to produce Figure 5. The standard set of VAX measurements (1989-1990) now included 1700 A and 3400 A but not 2500 A. We adjust the linear (geometry) term by matching the non-linear field at 1700 A and observe a range of non-linear strengths at 3400 A. With this presentation of these measurements we find good agreement (relative strength has range of about 9E-4) for the low current non-linear strength but slightly poorer agreement (12E-4) where saturation is important (3400 A).

Let us re-iterate the analysis steps which produce Figures 4 and 5. The FLATCOIL program measures flux changes from 0 A to the measurement current and reports the ratio of flux change to current change after correcting for integrator drift. We have converted this to an integrated strength at nominal current by multiplying by the nominal current, dividing by the loop width[1] and adding the remanent integral to that result. This provides an integral dipole field measurement. We then subtract a linear term such that the non-linear field at 2500 A (1700 A) matches that measured for ODM006 (ODM032) in 1995 using the downramp slope (without correcting for low field μ). We interpret the linear slope for ODM032 by assuming the gap is per design ($3''$) and calculating an effective length of $239''$. ODM006 has an L_{eff}/g which is smaller by 6.7E-4. Table 2 shows the factor by which an effective length of $239''$ must be scaled for each old measurement to match the 2500 A non-linear field of ODM006. Note that the factor for new ODM006 measurements is 0.99933. The ODM027-032 measurements from 1989-1990 require an adjustment of the linear term by more like 35$\pm$10E-4 in order to match the nonlinear strength of ODM032, including an adjustment of 25E-4 for the 1990 measurement of ODM032. Better information on the loop width calibration for the stretched wire might improve the agreement as could a better current calibration. We conclude that we can describe all of these measurements at high currents with the non-linear field measured for ODM006-1 (ODM032), the design gap of $3''$ and an effective length of $239''$. The uncertainty in this description is less than 0.4%.

5 Evidence for Adequate Current Measurements

The most precise dipole strength comparisons we can make are done by comparing them with a reference magnet. The FLATCOIL measurement system was designed to provide that capability. In addition to precise comparisons, the advantage of a reference magnet measurement is that the current measurement precision is of minor significance. By comparing absolute strength measurements against measurements relative to a reference magnet, one can obtain evidence concerning the reliability of the current measurement system. The MTF Stand C measurement system was upgraded with a second PEI power supply which was configured to provide current capability up to the full 3400 A nominal operating current. This became available for ODM measurements in January 1988. In Figures 6 and 7, we show strength mea-

[1] We will use stretched wire calibration numbers reported in email dated 22-JAN-1987. Perhaps the supports have been serviced since them. It is unlikely that changes larger than about 0.2% have occured.

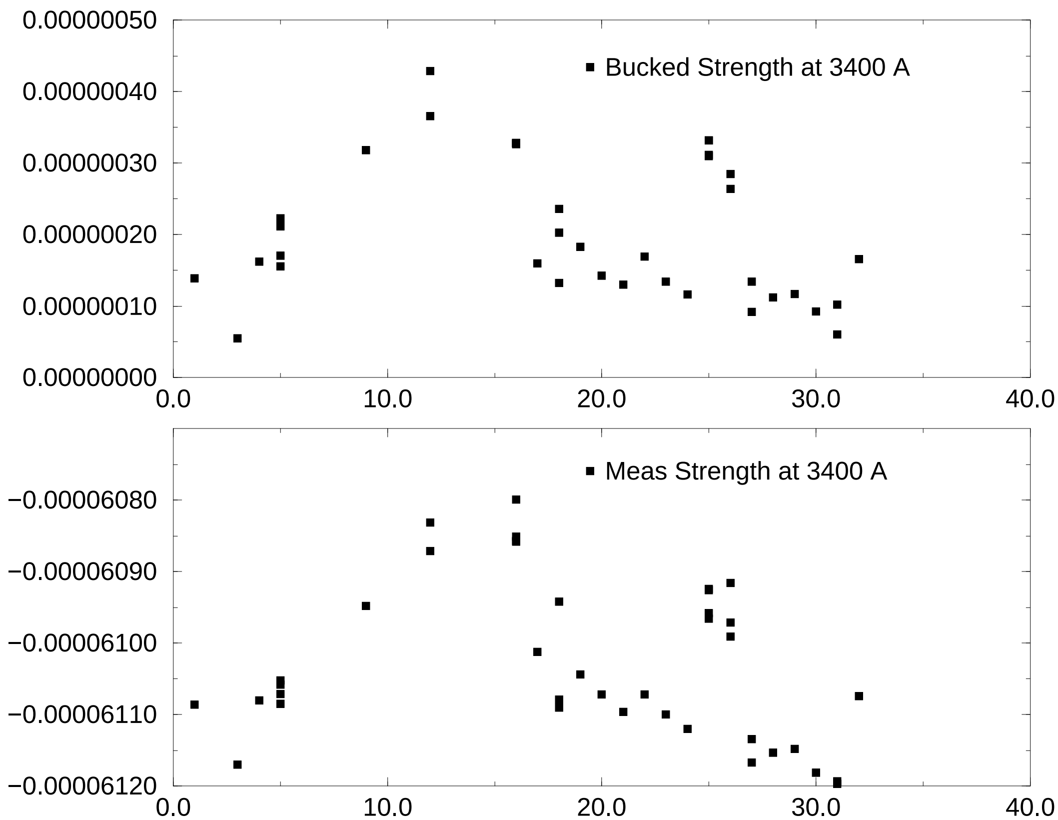

Figure 6: Strength of ODM dipoles at 3400 A. Strength *vs.* serial number is presented for both MEAS (absolute) and BUCK measurements. Vertical scale shows Flux/Current in $T - m^2/A$ without accounting for the width of the stretched wire loop.

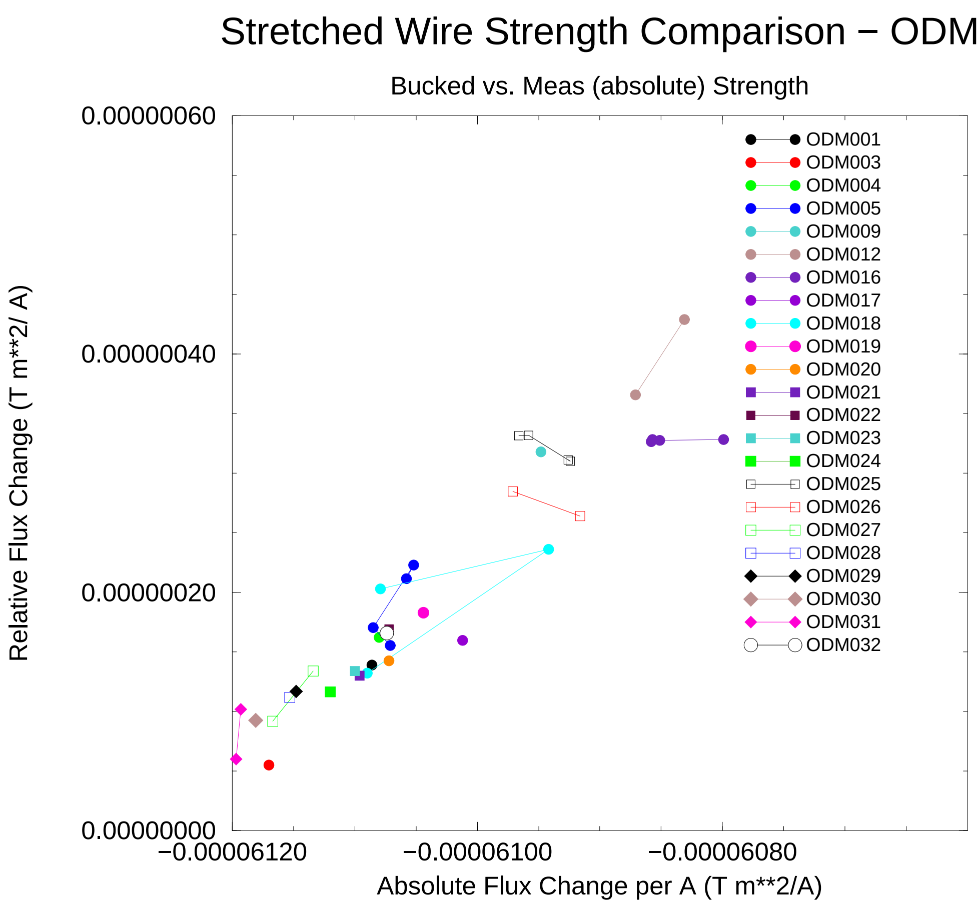

Figure 7: Strength of ODM dipoles at 3400 A. The MEAS (absolute)and BUCK are compared to show that good agreement. This confirms both the flux measurement system and current measurement system stability and reliability. Note that for ODM018, one of the measurements is of a magnet with one different half core so it should be expected that its strength is different.

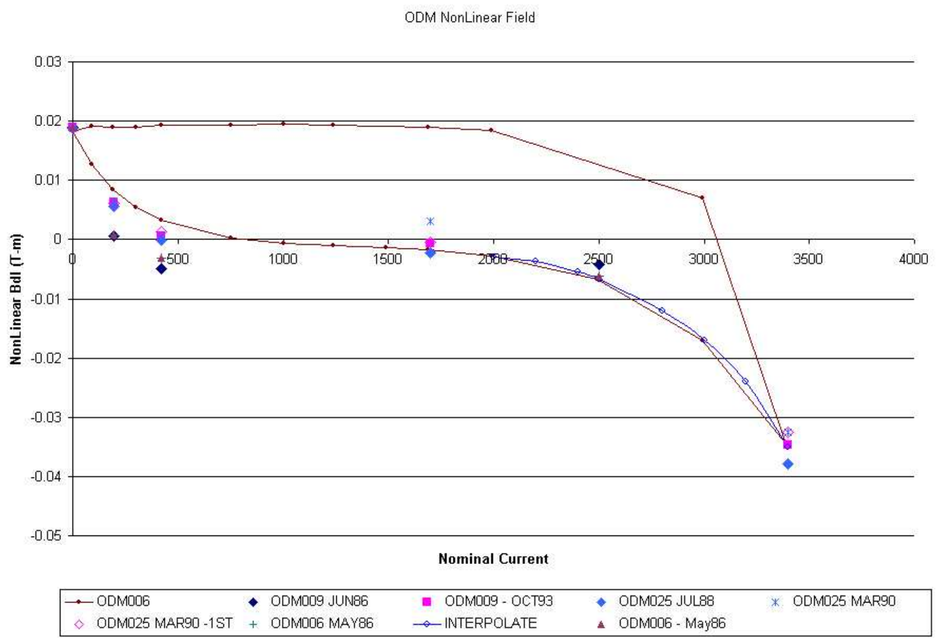

Figure 8: Non-linear strength of ODM009 plotted on graph of ODM006 non-linear strength. Non-linear field at 2500 A was matched to ODM006 measurements.

surements of ODM dipoles at 3400 A. In Figure 7, the values fall along the nearly diagonal line corresponding to correlated measurements with typical deviations of 5E-8 $T-m^2/A$ or a relative error of about 8E-4. The current measurement system provided stability to that level over that time period.

6 Results for ODM009

This work was carried out to allow us to validate the 1993 measurement results on ODM009. This magnet was installed in the Tevatron tunnel at F17 in April 2000 to be used as a switch between external beams and P-Bar production beamlines. Operating currents for 120 GeV operation were required. Since the magnet will be powered in common with a 'C' magnet (ICF), the installation geometry must be established with knowledge of the relative strengths of these magnets. The 120 GeV current will be near 2800 A.

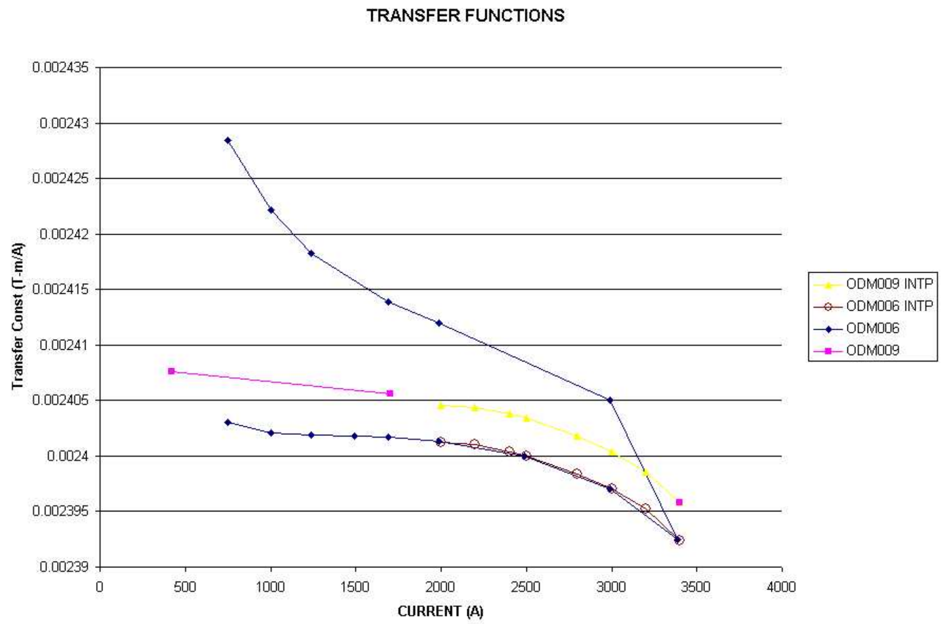

Figure 9: Transfer Constant (Strength/Amp) of ODM009 and ODM006

This magnet was built and tested in 1986. It was rebuilt and tested as ODM025 in 1988 and 1990. It was rebuilt with improved cooling in 1993 and measured as ODM009. We wish to document the results of the 1993 measurement for our present use. In Figure 8 we compare the non-linear strength of ODM006 and ODM009. The geometry adjustment (change in linear coefficient) is 1.0014, as shown in Table 2, with the same adjustment being made for all of the measurements of ODM009. Since even the CHISOX measurements of ODM006 do not provide detailed measurements at high fields, an interpolation was made using an 'eye-ball' fit on this figure to provide interpolated strengths for intermediate currents. For convenience of some users, this data is re-expressed as a transfer function in Figure 9. The interpolated non-linear strength was added to the linear strength and the result divided by the nominal current to provide the transfer function.Using the above analysis, the measured strength from each measurement of ODM009 (ODM025) are presented as transfer constants in Table 3.

Magnet	Date	194 A	420 A	1700 A	2500 A	3400 A
ODM009	5-Jun-86	0.002409	0.0023943		0.0024044	
ODM025	8-Jul-88	0.002435	0.0024057	0.0024047		0.0023949
ODM025	13-Mar-90	0.002438	0.0024092	0.0024058		0.0023965
ODM009	27-Oct-93	0.002439	0.0024076	0.0024056		0.0023958
ODM006	01-Dec-95	0.002445	0.0024105	0.0024017	0.0024000	0.0023925

Table 3: Transfer Functions of ODM009 from various measurements with 1995 measurement of ODM006.

7 Concerns and Conclusions

Before summarizing these results, it is useful to describe what was not done carefully in obtaining these results. This work was done with the goal of supplying an answer on a particular date, and although it was a multi-week effort altogether, it was not a careful, systematic job. A good survey of the results can be seen from this work. But the ultimate limits of the precision available from these measurement is not yet known. The following things should be done more carefully:

- The processes which swept data into the VAX DATATRIEVE databases permitted the measurers to exclude the most obviously bad data, but even the online comments and evaluations of the measurements were not examined for this work. Better results would be easily obtained by selecting the measurements which are to be used with some care.

- The calibration information has been applied without careful exploration of available information. Particularly the loopwidth calibrations of the stretched wire fixtures should be sought. The current calibration issue was addressed for the measurements after the power supply upgrade to provide 3400 A data became available. Some care should be applied to this issue for the complete data set.

- The distinction between nominal and measured current has been carefully maintained in the data used but that distinction was not carefully applied during this analysis. It is possible that small but significant improvements in these results would be obtained by a procedure which handled the current readback more consistently.

Despite the concerns identified above, the goal of this effort has been achieved. The strength of ODM009 has been reported at the currents required (near 2800 A and near 200 A) with a precision of 20E-4 (20 'units') or so. These are reported in Figures 8 and 9 as well as Table 3. Evidence exists that these measurement systems (both VAX-CAMAC and CHISOX) have provided strength precision of up to nearly $\times 10$ better than this for short periods within this time frame. We know of no feature of this data which demonstrates that a consistent analysis of all the available information would not achieve this precision.

To an accuracy of about 0.5%, the collection of all ODM dipoles appear to be alike (despite steel differences) if we consider only upramp data at 200 A or higher (parallel operation). Both the linear and the non-linear terms vary at a level somewhat smaller than this. As a group, the linear coefficient of the magnet strength is described by a gap of $3''$, an effective length of $239''$, 24 turns/pole with top and bottom poles powered in parallel. The resulting linear transfer function is 0.0024027 T-m/A. For this configuration, the non-linear fields are as shown in Figure 3 or 4 or 5 or 8. For all magnets, the complete transfer function will fall near the range shown in Figure 9

8 Acknowledgments

Although this work is only partly complete, there are many who must be acknowledged for their contributions. The MTF team who implemented both the VAX-CAMAC and the CHISOX measurement systems can remain proud of the successes of those efforts. Peter Mazur's leadership and his contributions to the hardware are acknowledged. The efforts of Kevin McGuire, Jim Pachnik, Julian Plymale, Rick Shenk, Lee Theriot and many others on the VAX software and data management continue to pay dividends. The CHISOX software team including Jim Sim, Kelley Trombley-Freytag, Penny Hall and others continue to provided a quality measurement software and data storage system. Efforts by Hank Glass and Dana Walbridge were crucial to these results. Gregg Kobliska provided reference materials on steel procurements. The measurement team at MTF provided their usual excellent effort. The long term interest of Stan Pruss in the results of magnet measurements continued to provide helpful materials in addition to his contributions to reviewing this work. Dave Johnson asked for these results and made use of them when they were provided so that the changes at F17 in April 2000 were implemented smoothly. Finally, I would like to thank Dave Harding for his continued helpful interaction on all aspects of measurements.

A Additional Notes on Steel

Steel ID	Year	Project	H_c (Oe)
MR Armco	<1970	Main Ring plus others	0.8
TeV I	1984-6	TeV I (PBar) plus others	3
Inland	1988	B3's to Enhance D0 Overpass	1.8
1989 Armco	1989	B3's for Aperture Improvements	0.62
LTV	1994	Main Injector Magnets(all types)	0.8

In keeping with the informal nature of this note, I will summarize some facts about the steel for which no documentation is publicly available. We have identified the following steel types which are relevant to the B3 dipoles. Many of the numbers are from a memo from Frank Turkot of Feb. 9, 1989[2]. This memo notes that the permeability at high fields is not isotropic with respect to the rolling direction. At 100 Oe, Inland showed B/H = 182 parallel but 178 cross while the New Armco showed B/H = 180 parallel and 172 cross. Similar measurement were made on the TeV I steel and it is also anisotropic.

For those interested in learning more about the steel procurements, there are steel specifications from various vintages. The Turkot memo references Fermilab Steel Spec. 8020-ES-186651. Issues like thickness, crown, hardness and insulation coating are discussed as well as the magnetic properties. Although the early Fermilab steel purchases always used inorganic coatings, there have been some organic coatings used to provide electrical insulation between laminations. This may be relevant to considerations about burning cores *vs.* other ways to recover cores from failed magnets.

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